Parabolic Troughs
Solar Hot Water Heaters

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## Abstract

Parabolic Troughs – Solar Water Heaters. DIEDRA VINSON (Eastern New Mexico University Portales, NM 88130). Dr. Andy Walker (National Renewable Energy Laboratory Golden CO 80401).

This paper focuses on concentrating solar water heating (SWH) using parabolic troughs, a renewable energy technology. Parabolic troughs only use direct solar radiation and are most effective in the Sunbelt region of the world and particularly in the southwest region of the United States. Parabolic troughs are long, curved mirrors that concentrates sunlight on a tube with a liquid inside that runs parallel in the focal line of the mirror. The liquid that is heated runs to a central tank or heat exchanger that heats potable water for large facilities such as hospitals, schools, and prisons. The particular trough system discussed is located at the Phoenix Federal Correctional Institute in Arizona. This solar water heater using parabolic trough technology preheats water for the electric water heater for this prison. From when it was installed in March 1999, to February 29, 2000, the system delivered 1,161,803 kWh (3,964 million Btu) of solar heat, saving the prison $7,780.56 and avoiding the emission 627,374 kg/yr of $CO_2$, 2,324 kg/yr of $SO_2$, and 2,297 kg/yr of $NO_x$. Trough systems have proven to be a viable, cost effective use of solar technology.

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**Yes** No

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## Introduction

Concentrating solar power allows us to harness the sun's energy to produce clean renewable energy. Parabolic trough solar water heating systems are most effective in the Sunbelt regions of the world and specifically in the open ranges of the southwestern United States where the atmosphere is clear and there is more direct radiation from the sun. Figure 1 illustrates the average daily direct solar radiation in $Wh/m^2/day$ for the United States (EREN, Concentrating Solar Power, 2002). Direct radiation rays are the shadow-casting beams coming parallel from the sun, so the curved shape of the mirror can focus the incoming beams or rays. Indirect solar radiation has been scattered by clouds or dust in the atmosphere, and these rays coming from random directions are not focused.

This renewable technology works in conjunction with traditional water heaters such as electric or gas. The solar preheats the water before it gets to the traditional heater, reducing electricity or fuel consumption. Solar water heaters are usually designed to meet 75-90% of the load. It is usually not cost-effective to install a solar water heater capable of meeting 100% of the load, as the storage tank and the collector area would have to be very large. Savings in electricity or fuel use are accompanied by savings in associated emission of $CO_2$, a global warming gas; $NO_x$, a precursor to smog, and $SO_2$, the source of acid rain, as well as other toxic emissions (personal communication, Andy Walker July 2002).

Implementation of parabolic troughs is economical for large hot water load institutions such as prisons, hospitals, and schools. The federal government has implemented solar water heaters in some large institutions to comply with executive order 12123, which issues the following directives regarding reductions in utility energy use and solar energy:

> "Sec. 202. Energy Efficiency Improvement Goals. Through life-cycle cost-effective measures, each agency shall reduce energy consumption per gross square foot of its facilities, excluding facilities covered in section 203 of this order, by 30 percent by 2005 and 35 percent by 2010 relative to 1985.
>
> Sec. 204. Renewable Energy. Each agency shall strive to expand the use of renewable energy within its facilities and in its activities by implementing renewable energy projects and by purchasing electricity from renewable energy sources. In support of the Million Solar Roofs initiative, the Federal Government shall strive to install 2,000 solar energy systems at Federal facilities by the end of 2000, and 20,000 solar energy systems at Federal facilities by 2010."

The installation of these systems is facilitated by of the Federal Energy Management Program (FEMP), which partners with Industrial Solar Technology (IST) of Golden, Colorado, currently the only manufacturer of these systems in the United States. By financing these systems using an Energy Saving

Performance Contract, IST installs, maintains, and monitors the system at no initial cost to the facility. The facility pays for the energy produced by the system at a 10% less than the current market price of conventional water heating methods (i.e. electricity). After 20 years of operation the federal facility will then own the system and the energy produced is free minus the operating and maintenance costs (personal communication, Ken May, June 2002).

One such installation by IST is at the Phoenix Federal Correctional Institution (FCI) in Arizona under the Federal Bureau of Prisons (FBP). The prison houses close to 1200 inmates and uses 21,000 gallons of hot water per day. Prior to installation of the trough system, conventional electricity was the sole source of power to heat water and 15% of the total electricity consumption for the Phoenix FCI was used for this purpose (Valenti, 1999). Now, with the parabolic trough solar water heater installed, the electricity bill to heat water has been reduced by 10% per month.

This paper will explain the technology and process involved with a parabolic trough solar water heating system and provides examples from the Phoenix FCI facility.

**Methods and Materials**

Parabolic troughs are curved shaped mirrors that have a pressurized absorber tube running parallel with the length of the trough. Direct sunlight reflects off of the mirror on to the absorber tube at the focal point (Fig 2). The sun is tracked east to west on a single north-south axis (Fig 3), to track the azimuth of the sun as it moves across the sky. Tracking the sun up and down around an East-West axis may also be used to track the sun as it rises and sets, but the N-S axis usually results in better performance during summer months or at low latitudes. During windy weather or when it is dark this electric tracking system turns the troughs downward. The absorber tube has a heat transfer fluid (HTF) that is water or a propylene glycol antifreeze solution and is pumped around a loop that flows between the collector tubes and the storage tanks. As heat is absorbed the HTF flows through a heat exchanger and directly heats potable water or a thermal storage tank (Fig 4). Propylene glycol is an ingredient of soda pop and candy bars, and should not be confused with the toxic antifreeze solution used in automobiles (EREN, Federal Technology Alert, Parabolic-Trough Solar Water Heating, 2002).

The Phoenix FCI solar water heating system is installed on 1.2 acres of land (Fig 5). The total net aperture of 120 parabolic troughs is 1,584 $m^2$ (17,040 $ft^2$). A steel shed houses two identical unpressurized water storage tanks, pumps, piping, controls, Btu-meters, and other additional equipment. The capacity of the identical storage tanks is 87 $m^3$ (23,000 gallons). Coiled heat exchangers on the solar side consist of 60 ft. long ¾" copper piping giving a heat exchange area of 21.1 $m^3$ (228 $ft^2$) per tank. The heat exchanger on the load side consists of 20 coils with a heat exchange area of 30.8 $m^2$ (332 $ft^2$) per tank. To mix the solar preheated water with cold water a tempering valve is used to achieve the desired delivery temperature of 55 C (132 F). A shutoff of solar water and cold-water bypass occurs at 140 F. The conventional electric water heaters are still installed to add heat if necessary to achieve the desired delivery temperature (May et. al, 2000).

**Results**

The System Monitoring Quarterly Operating Report No. 1: June 2001-March 2002 shows that the solar field itself had very few problems. Problems that did arise were due to prison personnel not following proper operational procedures, power failures, and distribution piping leakage.

Many of the problems were caused by the electrical and plumbing service to the system rather than the system itself. Table 1 shows the Operation and Maintenance issues and the action taken to correct the problems for this ten-month period, which completed the third year of operation.

Table 2 shows the Solar Resource and System Response. Most days are “clear days” and on average there were only two days per month with no sun. The “monsoon” season is evident for the months of July and August. October had only 10 clear days, which is very unusual for this month.

Table 3 illustrates Net Energy Delivery. 2001 was the poorest year for output for this system since its installation in 1999. In 1999, system output averaged 3,183 kWh/day and in 2001 averaged 2,786 kWh/day. Some of the factors were weather and operation problems. In spite of this, not including January 2002, the first four months have shown to meet the best year of energy delivery, which was in 2000.

**Discussion and Conclusions**

The benefits for the Phoenix prison consist of lowered utility and maintenance expenses, which totaled $7,780.56 in 1999. This facility also did not incur additional risk or expense of installing this system. The debt is being paid down on schedule to IST. In addition to monetary savings, emissions savings are estimated by EPA multipliers for Arizona as avoiding the emission of 627,374 kg/yr of $CO_2$, 2,324 kg/yr of $SO_2$, and 2,297 kg/yr of Nox (May, et. al., 2000).

Frank Foster the prison's facility foreman reported, " We save a bunch of money on (electric water heater) elements." Mr. Foster added, " We're saving a ton of money on maintenance calls and repairs. The complaints we've gotten from inmates about cold water have basically gone away (May et. al., 2000)." Trough systems have proven to be a viable, cost effective use of solar technology and Energy Performance Contracting has been demonstrated as a viable way to finance this promising use of solar energy.

**Acknowledgements**

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**References**


A. Walker, personal communication, July 2002

Barker, G. (2002). FCI-Phoenix Solar Water Heating System Monitoring Quarterly Operating Report No. 1: June 2001 – March 2002

EREN (Energy Efficiency and Renewable Energy Network). Technologies: "Concentrating Solar Power." Retrieved June 13, 2002 from the World Wide Web: http://www.eren.doe.gov/state_energy/technology_overview.cfm?techid=4

EREN (Energy Efficiency and Renewable Energy Network). Federal Technology Alert: "Parabolic – Trough Solar Water Heating." Retrieved June 21, 2002 from the World Wide Web: http://www.eren.doe.gov/femp/prodtech/paratrou_fta/html

Industrial Solar Technology: Putting the sun to work. (2002). Retrieved July 23, 2002 from the World Wide Web: http://www.industrialsolartech.com/trghtech.html

K. May, personal communication, June 26, 2002

May, K., Barker, G., Hancock, E., Walker, A., Dominick, J., Westby, B. (2002). Performance of a large parabolic trough solar water heating system at phoenix federal correctional institution. *Journal of Solar Energy Engineering* 122,165-169

Valenti, M. (1999). Solar Flares: Technology hones the efficiency of sun-powered energy systems. *Mechanical Engineering Power.* [Online]. Available: http:/www.memagazine.org/supparch/mepower99/solar/solar.html

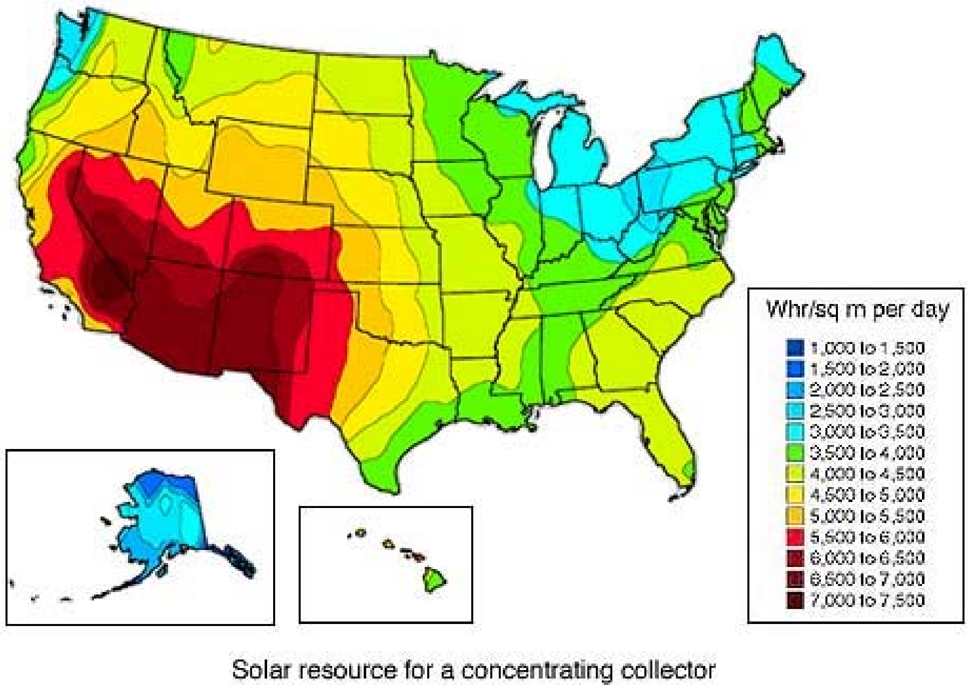


**Figure 1. Whr/sq m per day for the United States**

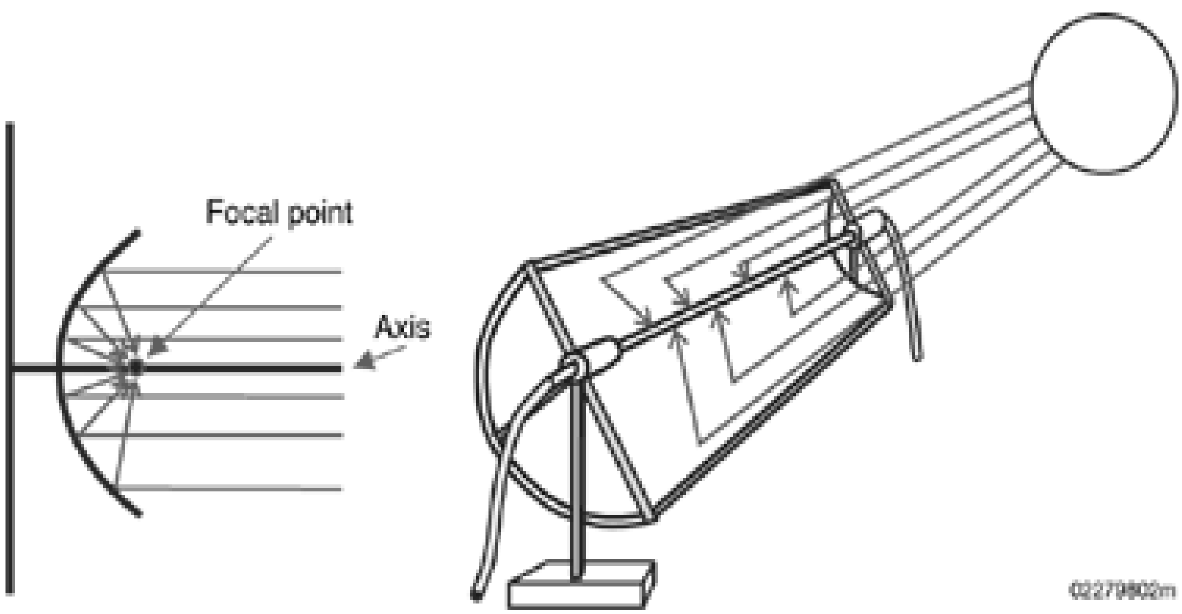


**Figure 2.Shows how the parabola works to concentrate energy on the focal point.**

**Figure 3. Ken May demonstrates the tracking system**

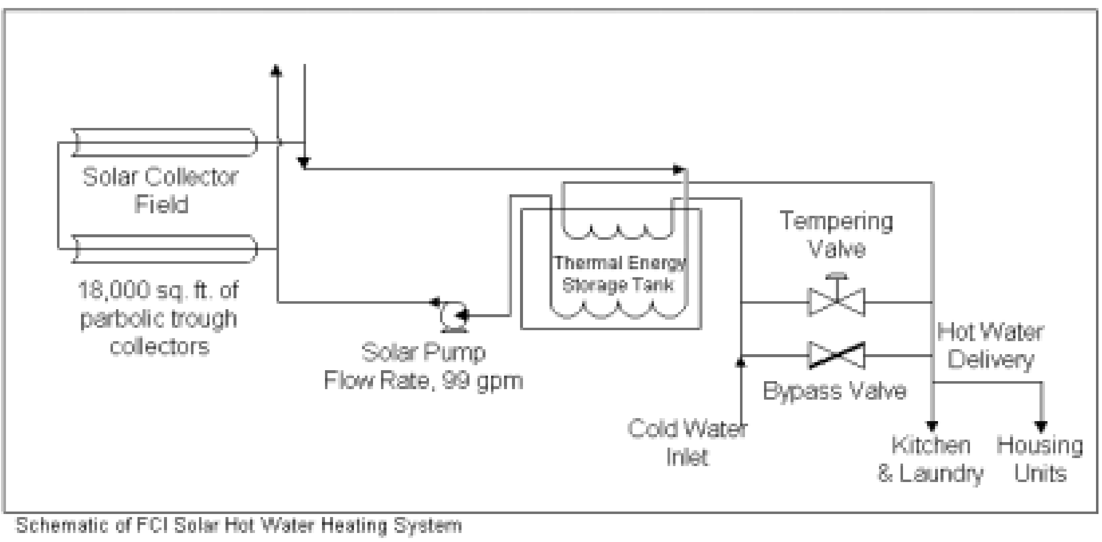


**Figure 4. Schematic Diagram of Solar Water Heating System**

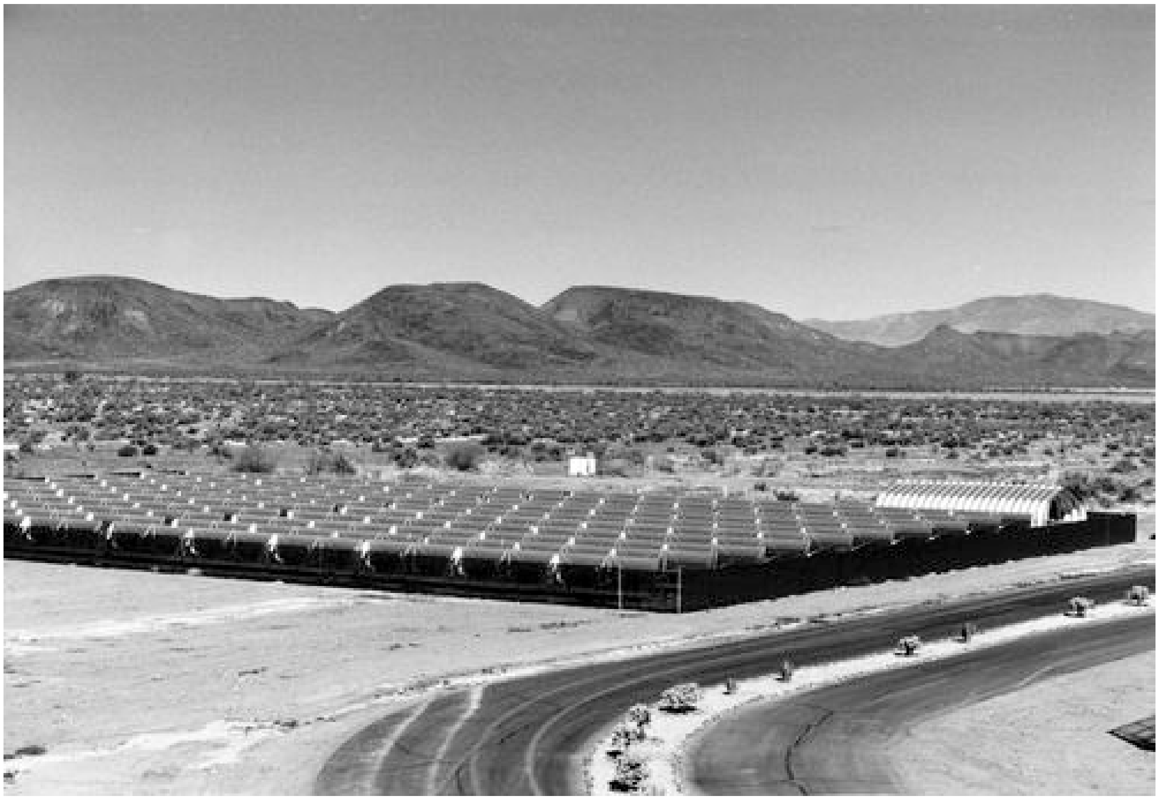

**Figure 5. Phoenix facility**

**Table 1**: **Operating and Maintenance Issues from June 2001**

| | | |
|---|---|---|
| May 31- June 8 | System down. Stagnation caused because of power interrupts. Backup pump flow not sufficient to remove heat to prevent boiling and discharge of PRV. Interrupt occurred ~ 1300 hours at peak output. Delay in detecting problem and in locating maintenance personnel. Lost 8 days of energy delivery | Refilled system with DI water and vented. No damage to selective surface. Collectors drove to stow on restoration of power. |
| Jun 14, 2001 | FCI shutdown system because of work on electrical system that supplies solar field and other loads. Lost one day of energy delivery. | FCI turned on system again. The emergency pump ran until the batteries discharged because they failed to turn it off during repair. |
| June 10-11 | System washed. Personnel at end of washing turned power off to west half of field. System stagnated for two days the sun traveled through focus twice each day. Boiled fluid, broke several glass and damaged selective surface. Only drive 1 selective surface is not damaged. Lost 2 days of energy delivery. | Refilled system with de-ionized water. Added chemical inhibitor and vented air. |
| June 12 | NW drive (No. 2) down. | Jumpered over temperature switch. |
| June 18-20 | Leak in plastic pipe to north of Pima Housing Unit. Flow to Units cut off. | Repaired leak in 2" line. Pipe split open. All other leaks had been at welded joints. |
| July 5, 2001 | Erroneous flow indication at night, detected June 19$^{th}$. | Bled air from differential pressure transducer |
| July 6 | System down 1 day—low pressure. Loss of fluid at pressure transducer | Tighten pipe at transducer and refilled system to operating pressure |
| Dec 19, 2001 | Leaking di-electric unions in solar lines into two storage tanks (minor fluid loss): detected July 14. | Replaced di-electrics with all-metal unions Dec. 19, 2001. |
| July 15- July 24 | Lockdown. Reduced hot water use. | |
| Aug. 8 | Water flow to Housing Units cut off Aug. 3-9. Leak between Yuma and Pima Units, and in vertical above ground section into a unit. | |
| Aug. 8 | System washed; depleted DI tanks used | Efficiency increased to 51.7% |
| Sept. 18 | Tempering valve not working properly resulting in reduced energy delivery and cycling of bypass valve. | |

| | | |
|---|---|---|
| Sept. 25 | Tempering valve set at fixed opening. | |
| Sept. 15 | Dirt on SUS from 11th. System shutting down for a short time. | Cleaned of bird dirt. |
| Oct. 15 | Replaced tempering valve controller | Tempering valve back in service. Valve to reverse acting: fails open |
| Oct. 23 | Repaired leak in flanged joint riser into Building C | |
| Oct. 28 | Fuse blows on battery charger. Field controller looses power. | Fuse replaced |
| Oct. 31 | Contractor digs up line to kitchen. Destroys 20 ft of pipe. Flow stopped. Leak repaired Nov. 6 | |
| Nov. 4-6, 2001 | Power spike blows fuse on battery charger. Field controller looses power. | Changed fuse |
| Nov. 15-16 | Battery charger fuse goes again. Cannot handle deep recharge of batteries | Installed higher amp fuse. |
| Nov. 16 | Emergency bypass valve solenoid controller chattering | Relay faulty. Replacement relay burns out. Removed relay from circuitry and ability to close off motor-driven valve to thanks. |
| Nov. 20 | Two leaks detected. On 27th water turned off to housing units. 29th repaired leak at riser into Navajo Unit. Water to Units still off. Serving kitchen only. | |
| Dec. 4 | System rain-washed in storm | |
| Dec. 5, 2001 | Repaired leak in “tee” to Navajo. 3” underground isolation valve installed to shut off flow to Pima and Yuma Units, if required. | |
| Dec. 12 | Coupling on NW drive motor slipping after rain. SUS twisting around pole so not facing exactly south. Reduced ser point on tanks after reaching 84C. | Tighten friction plate. Stopped SUS from twisting. |
| Jan. 2 2002 | System washed | Jan 4th eff. 49% |
| Jan. 9, 2002 | Added ball valves to replace gate valves to shut off solar flow in 3 to 5 housing units. Jan. 15: added valves in other 2 units. | |
| Jan. 9 | Leak behind Pima Unit at transition from 3” to 2” pipe Water turned off 8th. | Repair 16th. Flat stone found lodged in transition |
| Jan. 16 | Battery charger blows fuse. Low voltage shuts system down 18-21 | Reverted to old battery charger |
| Jan. 30 | System rain-washed. Added 50 gallon of propylene glycol anti-freeze to raise freezing point. | Efficiency Feb. 3rd, 47.7% |
| Feb. | IST personnel on site. Battery charger and | System washed and |

| | | |
|---|---|---|
| 20-27, 2002 | batteries replaced. Power supply for MC. Overload relay replaced in SW drive. Over temperature switch on NW back in service. Preventive maintenance: checked fasteners on bearings, drive system lubrication, added water to tanks, added fill line. | brushed. Eff. 51.1% |
| Feb. 26, 2002 | Leak to tee into Pima unit. Upstream pipe pulled during excavation. Replaced fittings on tee and about 10 ft of 2" pipe. | |
| March 4 | Leak 80 ft upstream of previous repair. Pipe pulled apart. Could have been result of pipe pull | Repair March 12, 2002 |

**Table 2: Solar Resource and System Response (from June 2001)**

| Month | Range of Direct | Normal Rad. W/m2/day | | | Days, no Operation | Reason for no operation |
|---|---|---|---|---|---|---|
| | >350 | 250-350 | 150-250 | <150 | | |
| June | 25 | 4 | 1 | 0 | 5 | Loss of fluid on stagnation |
| July | 15 | 9 | 5 | 2 | 1 | Loss of fluid, small leak |
| August | 20 | 4 | 6 | 1 | 0 | |
| September | 25 | 3 | 2 | 0 | 0 | |
| October | 10 | 9 | 9 | 3 | 0 | |
| | >300 | 200-300 | 100-200 | <100 | | |
| November | 16 | 6 | 5 | 3 | 4 | Loss of battery power to MC |
| December | 17 | 5 | 2 | 7 | 0 | |
| January | 16 | 5 | 2 | 8 | 4 | Loss of battery power to MC |
| February | 13 | 3 | 3 | 2 | 0 | 7 days of data missing |
| | >350 | 250-350 | 150-250 | <150 | | |
| March | 20 | 7 | 3 | 1 | 0 | |

**Table 3: Net Energy Delivery**

| Period | | Net Energy Delivery kWh | Parasitic Power kWh | Net Delivery kWh/day | Power Use KWh/day |
|---|---|---|---|---|---|
| 2001 | 5/30-6/29 | 71488 | 527 | 2306 | 17 |
| | 6/30-7/30 | 117127 | 817 | 3778 | 26 |
| | 7/31--8/30 | 81451 | 554 | 2627 | 18 |
| | 8/30-9/30 | 82203 | 721 | 2652 | 23 |
| | 10/1-10/31 | 73753 | 573 | 2379 | 18 |
| | 10/31-11/30 | 55704 | 653 | 1797 | 21 |
| | 11/30-12/31 | 71297 | 510 | 2300 | 16 |
| 2002 | 1/l/02-1/31/02 | 61330 | 529 | 1978 | 17 |
| | 2/1-2/28/02 | 93440 | 871 | 3014 | 28 |
| | 3/1-3/31/02 | 107127 | 522 | 3456 | 17 |
| | 4/1-4/30 | 115692 | 849 | 3732 | 27 |